THIRD QUARTERLY PROGRESS REPORT

on

EXPLORATORY STUDIES OF MECHANICAL CYCLING FATIGUE BEHAVIOR OF MATERIALS FOR THE SUPERSONIC TRANSPORT

to

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

April 15, 1963

by

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May 15, 1963

Dr. T.L.K. Smull
National Aeronautics and
Space Administration
1512 H Street, N.W.
Washington 25, D. C.

Dear Dr. Smull:

Task Order Contract No. NASr-100(01):
Exploratory Studies of Mechanical
Cycling Fatigue Behavior of Materials
for the Supersonic Transport

This is the third quarterly status report on this contract. The present report covers work for the period January 1 to April 15, 1963. It describes the work done and in progress, and outlines plans for the remainder of the program.

Very truly yours,

Walter S. Hyler
Research Associate
Solid and Structural Mechanics

WSH:slp
Enc. (45)

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EXPLORATORY STUDIES OF MECHANICAL CYCLING
FATIGUE BEHAVIOR OF MATERIALS FOR
THE SUPERSONIC TRANSPORT

INTRODUCTION

The Battelle effort is part of the National Aeronautics and Space Administration program to provide information pertinent to the development of a commercial supersonic transport (SST) with a cruising speed of approximately Mach 3. The materials area is one of the major ones in which background information necessary for design decisions is lacking. One of the unknown facets of this area is the importance of long-time thermal effects when superimposed on the usual cyclic stresses to which such aircraft may be subjected. Since the skin temperatures of leading edges under cruise conditions are expected to be as high as 600 F, possible metallurgical instability of materials is a factor requiring study.

The objective of the Battelle research program is the exploration of some of the problems associated with mechanical cycling of SST materials as affected by possible metallurgical instability. Information from this program will (1) serve as a guide for selecting materials for the SST, and (2) direct attention toward the nature and needs of further fatigue studies for the SST development.

SUMMARY

Abstract 17221 over

This report describes the experimental work completed thus far in the program and indicates the present status and plans for the remainder of the contract period.

Tensile stress-strain data have been obtained at -100 F and at 550 F on both the AM 350 and the Ti-8Al-1Mo-1V alloys. These supplement similar data obtained earlier at room temperature.

The generation of fatigue data for both alloys has continued. S-N plots have been obtained for unnotched and notched (K_T = 4.0) specimens, at room temperature, -110 F, and 550 F. For the AM 350 steel, S-N plots are nearly complete, including data for both as-received material and stress-temperature exposed material. The latter data, obtained with specimens exposed for 1000 hours at 550 F and 40-ksi mean stress before the fatigue experiments, indicate a slight lowering of the fatigue limit due to the exposure. This apparent trend will be investigated further with specimens exposed 3000 hours. Tests with exposed titanium alloy specimens will be made in the next quarter.

Center-notched specimens of AM 350 steel were made in order to investigate residual-strength and crack-propagation behavior with respect to several variables including temperature, alternating stress, cycling rate, stress-temperature exposure, etc. Some 30 specimens have thus far been cracked in fatigue to specified crack lengths for the residual strength experiments; crack lengths versus number of cycles

are being recorded during these experiments. On the basis of the limited data obtained so far, some tentative conclusions can be drawn concerning the effects of temperature, alternating stress, and previous stress-temperature exposure on crack-propagation rate. Previous exposure for 1000 hours appears to reduce significantly the number of cycles required to initiate cracks, and also to produce cracks of a given length, at least up to 3/16-inch length (tip to tip).

Replicas of AM 350 fatigue-fracture surfaces produced at three different stress levels were studied with the electron microscope. Striation markings were observed and their spacings were compared with the measured crack-propagation rates. It was tentatively concluded that each striation represents one fatigue cycle. Additional studies are in progress.

Eleven center-cracked AM 350 sheet specimens have been tested in tension at room temperature to measure residual strength and fracture toughness. These preliminary results suggest that both exposure and specimen orientation influence the residual strength, while the temperature and stress level employed to introduce fatigue cracks have very little effect on residual strength.

The relatively high ductility of the AM 350 precluded determination of K_c values; however, K_{Ic} values were calculated, based upon the original crack length and the stress at which the load-elongation curve deviated from linearity. Preliminary results suggest that K_{Ic} is influenced by the ratio of crack length to specimen width, specimen orientation, and the temperature and stress level employed to introduce cracks. Exposure apparently has very little effect on this parameter.

EXPERIMENTAL WORK

Stress-Strain Behavior of Sheet Materials at -100 F and 550 F

Previous quarterly reports presented tensile stress-strain data for the AM 350 steel and the Ti-8Al-1Mo-1V alloy at room temperature. During this quarter similar data have been obtained for both alloys at -100 F and at 550 F. These data, presented in detail in Table 1, are summarized and compared with the room-temperature data in Table 2. The most striking aspect of these data is the large decrease of elongation of the AM 350 specimens with elevated temperature.

Fabrication of Center-Notched Specimens

The residual strength and crack-propagation studies are being conducted using specimens 2 inches wide by 8 inches long and having central, slit-type notches. Details of the design, shown in Figure 10 of the second quarterly report, specify a slit about 0.010 inch wide and 0.120 inch long. The fabrication procedure involves three steps:

(1) Milling of the external dimensions, and drilling and reaming the holes for loading

TABLE 1. TENSILE DATA FOR LONGITUDINAL SPECIMENS OF AM 350 AND Ti-8Al-1Mo-1V SHEET MATERIAL AT -100 F AND 550 F

Specimen	Thickness, inch	Test Temperature, F	0.2 Per Cent Offset Yield Strength, 10^3 psi	Ultimate Tensile Strength, 10^3 psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
			AM 350			
828	0.051	-100	221	273	20.5	27.0
829	0.051	-100	221	272	20.0	29.2
8210	0.051	+550	185	202	4.0	25.4
8211	0.051	+550	183	199	3.5	25.2
			Ti-8Al-1Mo-1V			
TA 828	0.0415	-100	165	178	11.5	20.1
TA 829	0.0415	-100	166	179	12.5	20.0
TA 8210	0.0415	+550	98	125	9.0	16.0
TA 8211	0.0415	+550	97	124	10.0	17.4

TABLE 2. SUMMARY OF TENSILE STRESS-STRAIN DATA FOR LONGITUDINAL SPECIMENS OF AM 350 STEEL AND Ti-8Al-1Mo-1V ALLOY

Temperature, F	0.2 Per Cent Offset Yield Strength, 10^3 psi	Ultimate Tensile Strength, 10^3 psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
		AM 350		
-100	221	272.5	20.2	28.1
RT	221	233	21.1	27.8
550	184	221	3.7	25.2
		Ti-8Al-1Mo-1V		
-100	165.5	178.5	12.0	20.0
RT	139.7	152.3	12.9	18.8
550	98.0	124.5	9.5	16.7

(2) Roughing in a slit in each specimen by spark discharge using a jig to insure centering and alignment of the slit in the specimen

(3) Grinding the ends of the slit in each specimen to achieve good geometrical definition of the slit ends, and specified length and centering of the slit.

Figures 1 and 2 show a specimen mounted in the jig in position below the tool of the sparking apparatus. The base plate of the jig is used also in the grinding apparatus, as shown in Figure 3. The grinding is done by a wire drawn back and forth through the slit, an abrasive slurry being kept on the wire. The grinding is stopped automatically when the grinding has proceeded to a point where the lever, one end riding the wire, is permitted to make electrical contact on its lower end. The upper end of the lever and a slit are shown in close-up in Figure 4. When grinding is finished on one end of the slit, the specimen is turned over on the jig to grind the other end of the slit.

Some 60 AM 350 center-notched specimens have been made. Examination of the finished notches shows them to be uniformly good and to have radii of 0.0045 inch; the slit lengths are 0.122 ± 0.002 inch. The elastic stress concentration factor for these specimens is estimated to be 7.8, using relations derived by Inglis(1) and by Dixon(2), as reported by Gerard(3)*.

Both unexposed and 1000-hour-exposed specimens of AM 350 are presently being precracked by fatigue loading. Various stress amplitudes, frequencies, and temperatures are being used in producing the cracks. Specimens with different crack lengths are being prepared, with the major emphasis being placed on specimens containing long (3/4-inch) cracks**. Most of the specimens are being cracked on a 10,000-pound, mechanical-loading, Krouse fatigue machine operating at about 1200 cycles per minute. During cracking the net section stresses are held constant within ±10 per cent of the nominal values. Crack-propagation rates are measured for each specimen by periodically stopping the fatigue machine. With the specimen at room temperature the measurements are made by preparing cellulose acetate replicas of the crack; from the replicas the crack length can be accurately measured to the nearest 0.001 inch. At -110 F and at 550 F, the measurements will be made with a measuring microscope focused on the crack through a window in the enclosure.

Crack-Propagation Rates

Table 3 summarizes some of the crack-propagation data obtained thus far. In this table only the number of cycles pertaining to 3/16-inch cracks** are shown, although for many of the specimens the cracks were propagated to 3/8-inch or 3/4-inch lengths. The total number of cycles to develop cracks 3/16 inch long were read in each case from plots of cycles versus crack length; the number of cycles to initiate cracks was estimated by extrapolating in each case from the first pair of data points after actual initiation had occurred.

*References appear at end of report.

**Crack length is defined here as the tip-to-tip length.

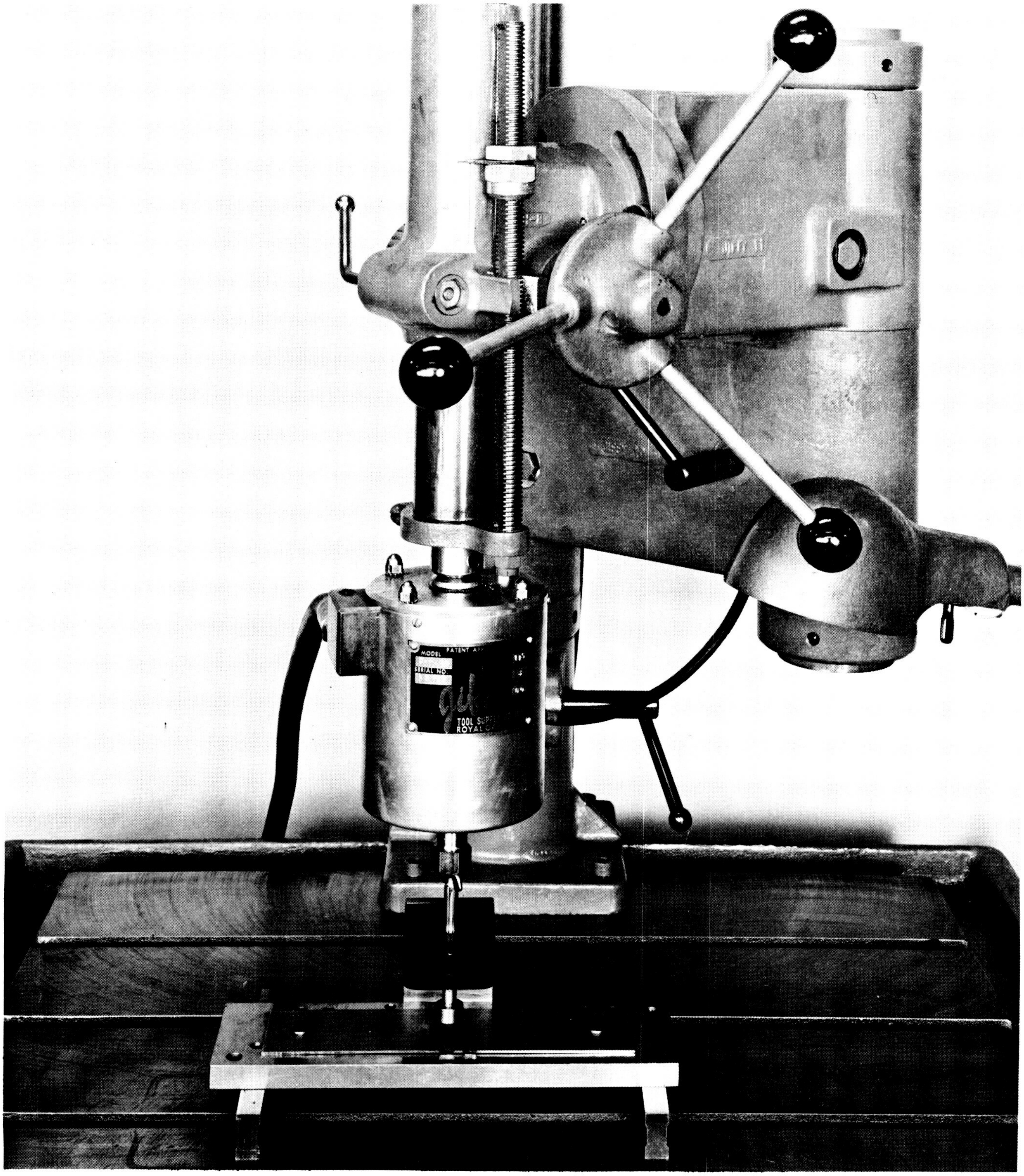

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FIGURE 1. SPARK APPARATUS FOR PRODUCING NARROW SLOTS IN SPECIMENS, SHOWING SPECIMEN IN JIG BELOW TOOL

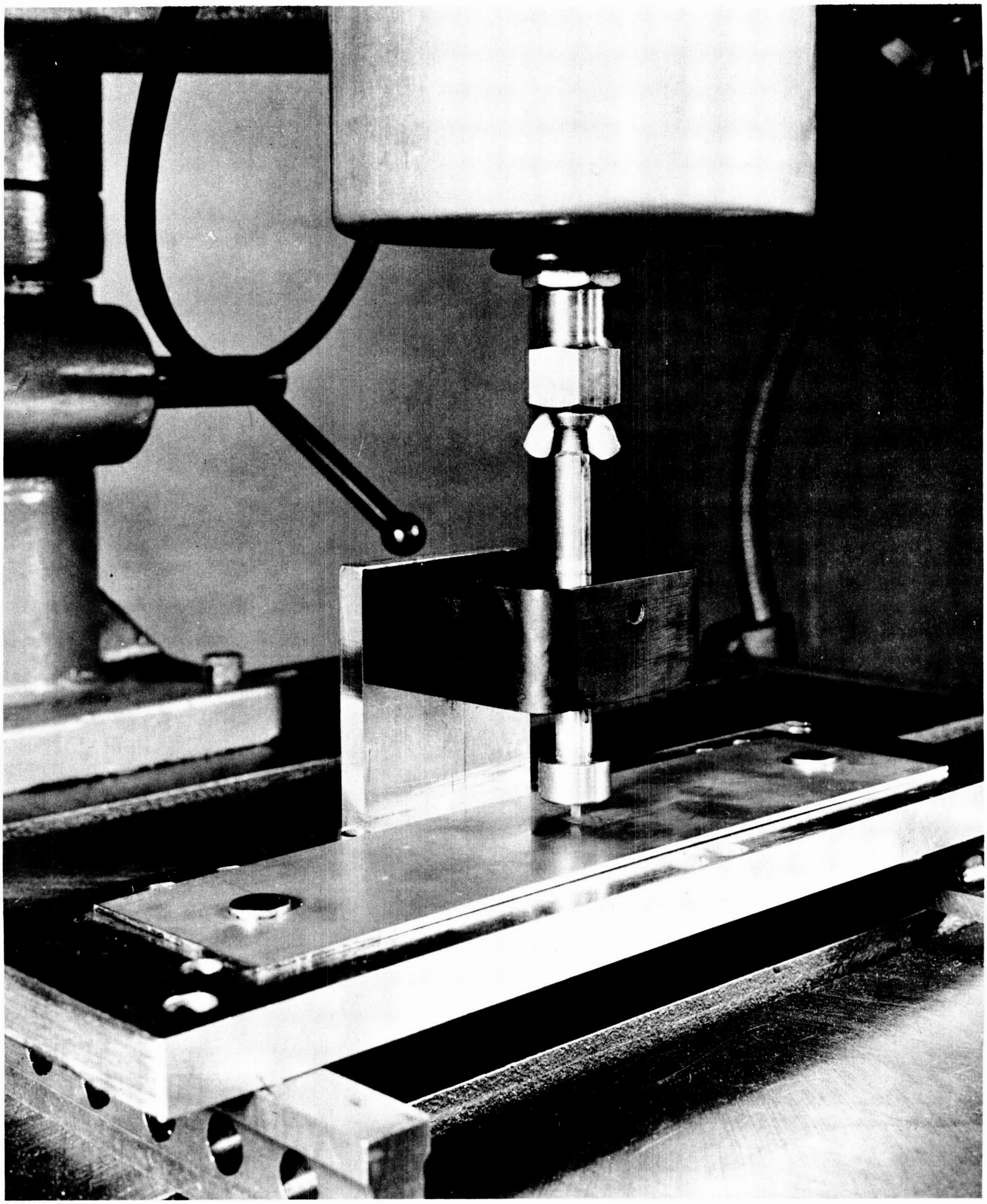

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FIGURE 2. CLOSE-UP VIEW OF SPARK APPARATUS

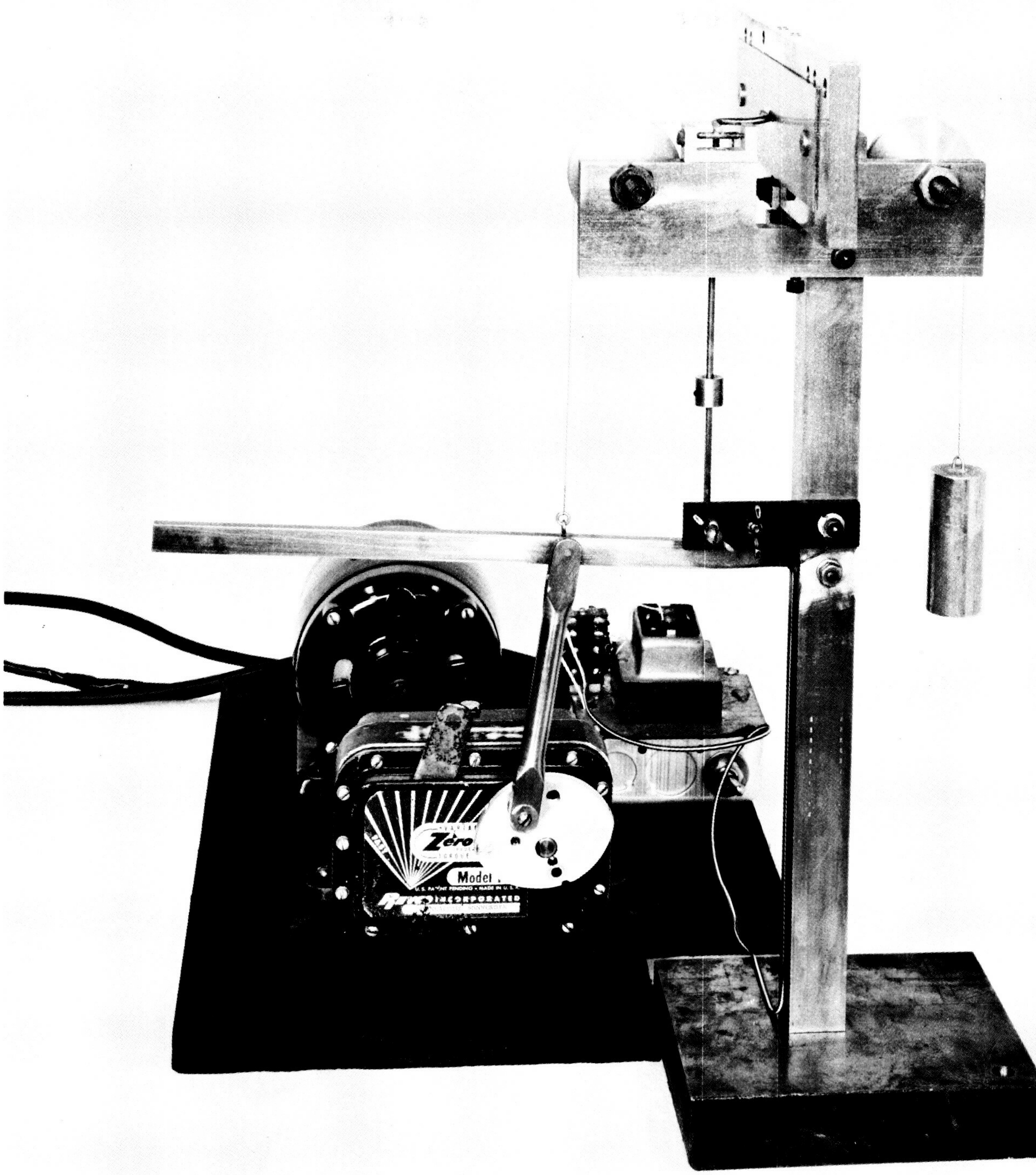

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FIGURE 3. APPARATUS FOR GRINDING ROOTS OF NOTCHES

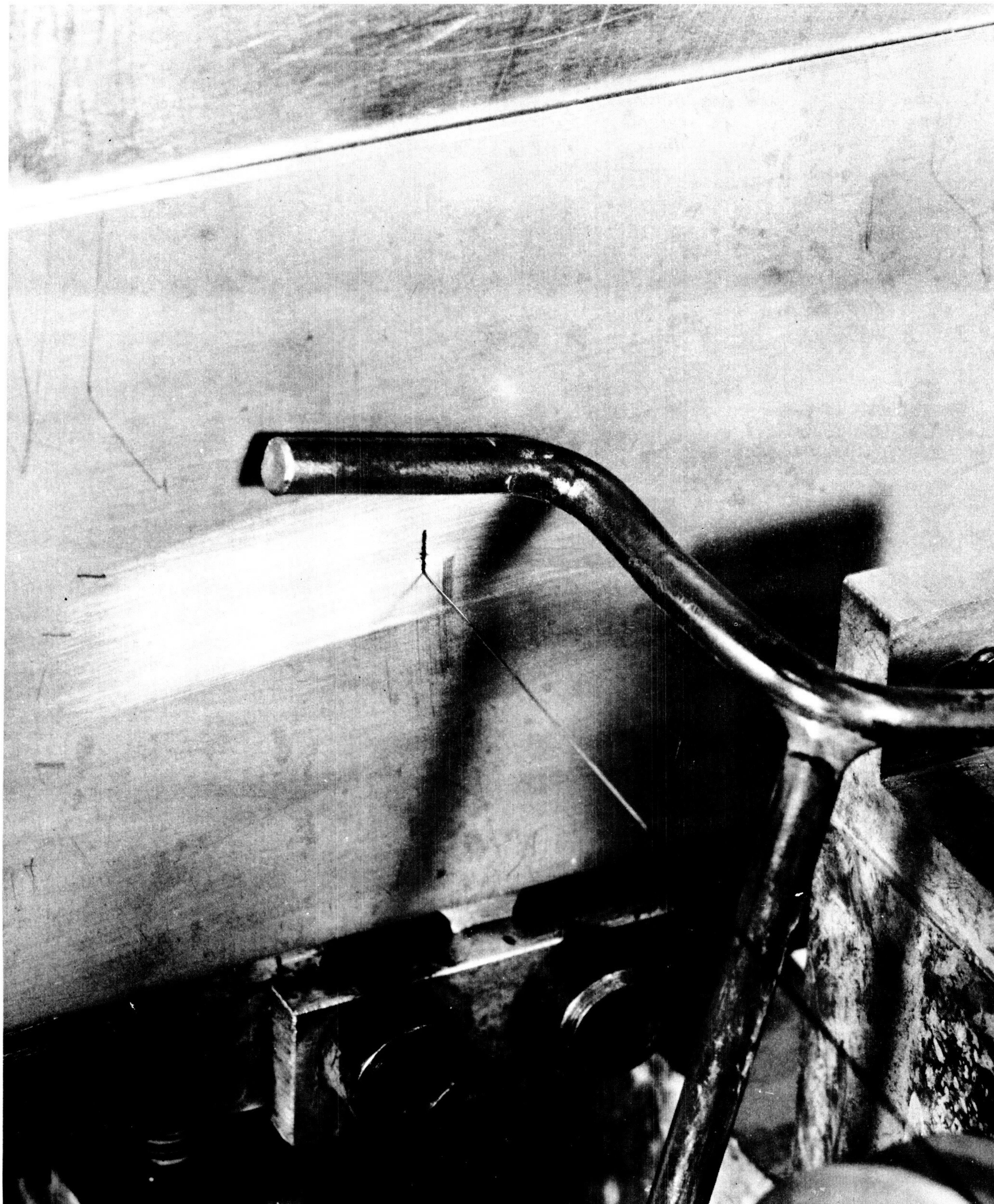

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FIGURE 4. CLOSE-UP VIEW OF ROOT GRINDING APPARATUS

TABLE 3. SUMMARY OF CRACK PROPAGATION DATA OBTAINED IN PREPARING RESIDUAL STRENGTH SPECIMENS OF AM 350

(All Longitudinal Specimens)

Conditions	Number of Experiments	Total Cycles to 3/16-inch Crack Length[a] Mean	Total Cycles to 3/16-inch Crack Length[a] Standard Deviation	Cycles to Initiate Mean	Cycles to Initiate Standard Deviation	Cycles for Propagation Mean	Cycles for Propagation Standard Deviation
1. Fatigued at RT 40 ksi mean 30 ksi alternating Unexposed	10	8,100	890	3,430	700	4,670	840
2. Fatigued at RT 40 ksi mean 30 ksi alternating Exposed 1000 hours	8	7,410	1,100	2,370	690	5,040	640
3. Fatigued at 550 F 40 ksi mean 30 ksi alternating Unexposed	3	6,600	700	1,830	580	4,770	650
4. Fatigued at 550 F 40 ksi mean 30 ksi alternating Exposed 1000 hours	1	5,400	--	2,000	--	3,400	--
5. Fatigued at RT 40 ksi mean 55 ksi alternating Unexposed	1	3,400	--	0	--	3,400	--
6. Fatigued at RT 40 ksi mean 15 ksi alternating Unexposed	1	56,500	--	35,500	--	21,000	--

(a) Tip-to-tip length.

In spite of the large standard deviations, the room-temperature data indicate apparently significant differences between the specimens exposed to temperature and stress for 1000 hours and the unexposed specimens; both the number of cycles to initiate and the total number of cycles to achieve a crack length of 3/16 inch are less for the exposed specimens. However, the propagation rates for the exposed and the unexposed specimens at room temperature are not significantly different at the 1 per cent level of significance according to the rank test.

Examining the data in Table 3 for fatigue at 550 F, there is an obvious temperature effect (see Condition 3) on the number of cycles to initiation and on the total number of cycles to generate the cracks (to 3/16-inch length). Again, the propagation rate does not appear to be significantly different at 550 F than at room temperature.

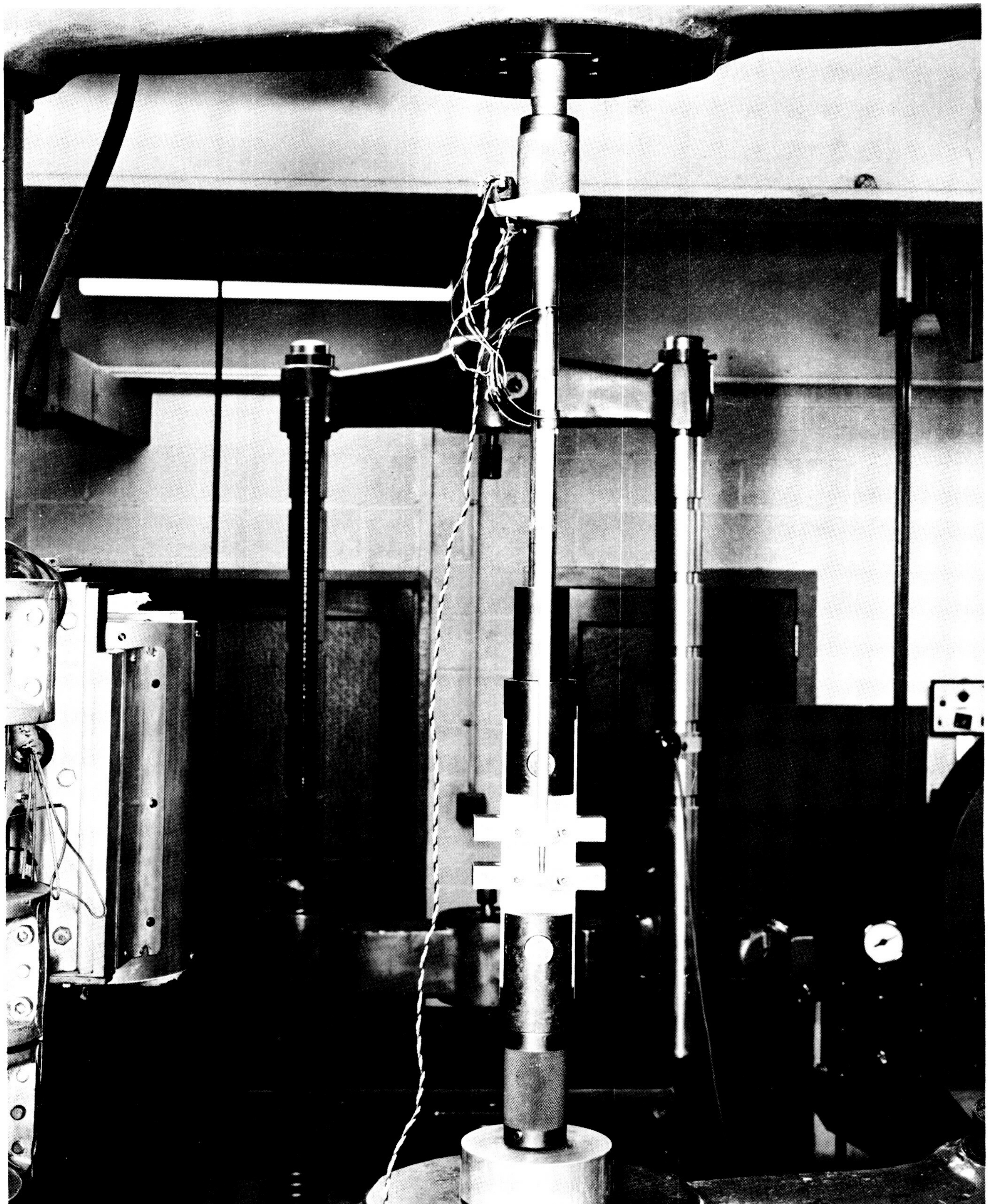
Comparison of Conditions 1, 5, and 6 indicates the effect of alternating stress level on initiation, crack-propagation rate, and total cycles to produce 3/16-inch cracks. The number of experiments is too small to determine a functional relationship, but the sensitivity of crack initiation and propagation to alternating stress level is large, as one would expect.

Tensile Tests of Center-Cracked Sheet Specimens

Center-cracked sheet specimens of AM 350 were tested in tension to determine the residual static strength. Attempts were made also to evaluate the fracture-toughness parameters, K_{Ic} and K_c, for the same specimens. Calculation of K_{Ic} requires knowledge of the initial crack length and the load at which the crack begins to grow, while calculation of K_c requires knowledge of the load and crack length at the onset of rapid crack propagation. To make these measurements, a compliance gage (Figure 5) was constructed that was similar in performance to the one described by Boyle[4]. Elongation is measured between two points located 0.667 inch above and below the center crack and centered with respect to the width. The elongation is transmitted by a rod-and-tube arrangement to two beryllium-copper loops, to which electrical-resistance strain gages are attached. These remote gages make it possible to use the compliance gage at temperatures other than ambient. The four strain gages are connected as a full bridge through an SR-4 converter to the recording drum of a hydraulic-testing machine. The compliance gage has been calibrated to make it possible to determine the crack length of a specimen from the slope of the load-elongation curve.

Tensile testing of center-cracked specimens has not been completed. However, several room-temperature tests have been conducted, with interesting results. In conducting the tests, a constant head speed of 0.02 inch per minute was used for all specimens. As loading progressed, the areas immediately adjacent to the crack tips were watched carefully for the first sign of "dimpling". The load at which dimpling became observable was recorded. The growth of the plastically deformed zone and growth of the crack also were observed closely during each test at room temperature.

For all specimens tested to date, the load-deflection curve was observed to be initially linear, but began to deviate from linearity at nearly the same load as that at which dimpling was observed at the crack tips. In no instance was a sudden burst of strain detected (sometimes called "pop-in"), as has previously been reported for other



N98455

FIGURE 5. COMPLIANCE GAGE ATTACHED TO PRECRACKED SHEET SPECIMEN

high-strength materials. The curve continued to bend over gradually until a maximum in the load was observed. Beyond this point, the crack began to extend slowly and the load dropped off, finally ending with fracture of the specimen. Because the plastically deformed zones extended to the specimen edges prior to appreciable crack growth, calculations of K_c were unwarranted. However, K_{Ic} calculations were carried out on the assumption that the start of crack growth corresponded with the deviation from linearity of the load-deflection curve (and probably also with the occurrence of dimpling), even though no crack growth was detected on the surface. Precise determination of this point on the curve is difficult and, hence, the calculated K_{Ic} values are subject to some uncertainty.

The results of room-temperature tensile tests on center-cracked AM 350 sheet specimens are presented in Table 4. One objective of these tests was to determine the effect on residual strength of crack length, exposure to stress at elevated temperature, and fatigue stress amplitude and temperature employed in preparing the center crack. To facilitate comparison of the results of Table 4, they are shown graphically in Figure 6. The method of plotting the results was suggested by Bockrath and Glassco[5], who found that a wide variety of test data, if plotted as log σ_N/σ_u versus log ℓ/W, fall on a straight line.* By extrapolating this straight line, it is possible to determine a crack length below which the material will not be weakened; this is expressed as ℓ_o/W. Large values of ℓ_o/W are indicative of insensitivity to relatively large cracks. The slope of the line, $-1/a$, is indicative of the rate at which the material becomes weakened as crack length increases; large values of "a" are desirable.

Referring to Figure 6, several tentative observations can be made:

(1) Unexposed longitudinal specimens of AM 350 are weakened by cracks whose ℓ/W ratio exceeds 0.00074; however, the extent of weakening is very slight, even at large crack lengths, as indicated by the large <u>a</u> value of 75.3.

(2) 1000-hour-exposed longitudinal specimens of AM 350 will withstand slightly longer cracks, up to $\ell/W = 0.064$, without being weakened; however, for cracks of $\ell/W > 0.38$, the exposed specimens will be weakened more than unexposed specimens.

(3) The residual strength at $\ell/W = 0.375$ does not appear to be changed significantly by introducing the fatigue crack at 550 F instead of at room temperature.

(4) The residual strength at $\ell/W = 0.375$ is not altered significantly by changing the fatigue stress amplitude between 15,000 and 55,000 psi (superimposed on 40,000-psi mean stress).

(5) At $\ell/W = 0.375$, the residual strength of transverse specimens is decreased to a greater extent than that of longitudinal specimens.

These are tentative observations only and may have to be revised as more data become available.

* σ_N is defined in Table 4; σ_u is the ultimate tensile strength; ℓ/W is the ratio of crack length to specimen width.

TABLE 4. RESULTS OF TENSION TESTS ON CENTER-CRACKED AM 350 SHEET SPECIMENS

Specimen	Orientation	Crack Length, inches	Fatigue Stress Amplitude	Fatigue Temperature, F	Exposure Time, hours	σ_N,(a) 10^3 psi	σ,(b) 10^3 psi	K_{Ic}, 10^3 psi $\sqrt{\text{in.}}$	Fracture Appearance: Fatigue	Fracture Appearance: Tensile
6310	L	0.188	Medium(c)	75	None	218	197	49.9	Flat	Full shear
834	L	0.188	Medium	75	1000	*	*	48.8	Flat	--
6313	L	0.375	Medium	75	None	216	175.5	61.7	Flat	Full shear
8320	L	0.375	Medium	75	1000	221	179.5	66.8	Flat	Full shear
6317	L	0.751	Medium	75	None	214	134	74.3	Flat	Full shear
8311	L	0.747	Medium	75	1000	214	134.3	67.3	Flat	Full shear
7311	L	0.749	Low(d)	75	None	212.5	133	69.7	Flat	Full shear
836	L	0.757	High(e)	75	None	213	132	88.8	Flat	Full shear
7322	T	0.751	Medium	75	None	195	122	69.7	Flat	Full shear
738	L	0.744	Medium	550	None	214	134.5	78.8	Flat at start, changing to full shear at tips	Full shear
833	L	1.009	Medium	550	1000	210	104	79.5	Ditto	Full shear

(a) $\sigma_N = \dfrac{\text{maximum load}}{(\text{width-crack length}) \times \text{thickness}}$.

(b) $\sigma = \dfrac{\text{maximum load}}{\text{width} \times \text{thickness}}$

(c) 40,000-psi mean stress plus 30,000-psi alternating stress.

(d) 40,000-psi mean stress plus 15,000-psi alternating stress.

(e) 40,000-psi mean stress plus 55,000-psi alternating stress.

* Specimen yielded and failed in grips.

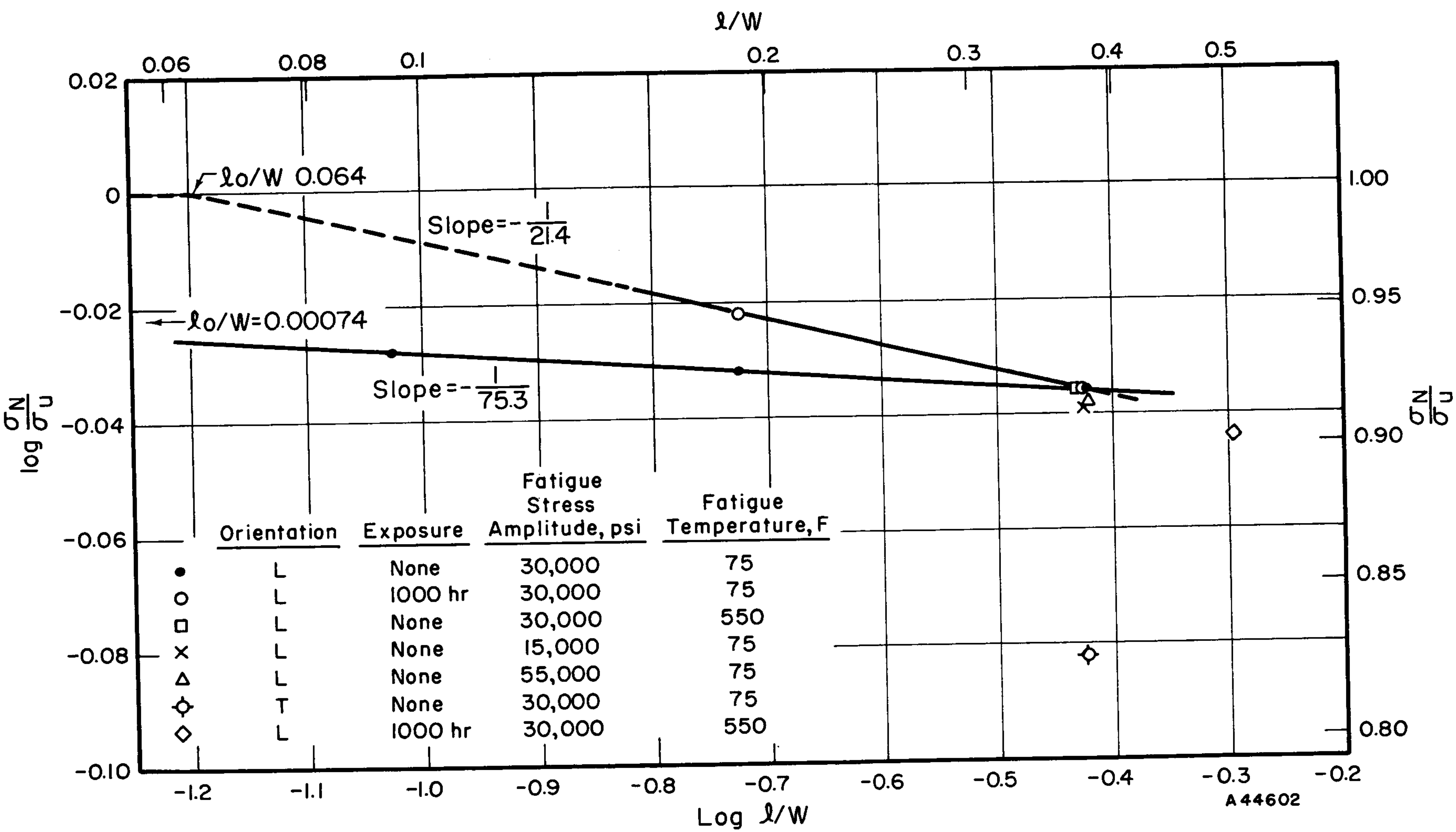


FIGURE 6. STRENGTH OF CENTRALLY CRACKED AM 350 STEEL SHEET SPECIMENS (2 INCHES WIDE BY 0.051 INCH THICK) AS A FUNCTION OF CRACK LENGTH

With regard to the calculated plane-strain fracture-toughness values, K_{Ic}, reported in Table 4, several tentative observations can be made:

(1) The calculated value of K_{Ic} increases as the ratio of crack length to specimen width increases.

(2) 1000-hour exposure has little, if any, effect on the calculated K_{Ic} value.

(3) Fatigue cracks introduced at high stress appear to give a higher K_{Ic} value than the cracks introduced at medium or low stresses.

(4) Fatigue cracks introduced at 550 F lead to a higher K_{Ic} value than do cracks introduced at room temperature.

(5) Transverse specimens exhibit a slightly lower value of K_{Ic} than do longitudinal specimens.

Additional studies at -100 and +550 F are in progress.

Fatigue Behavior of AM 350 and Ti-8Al-1Mo-1V Alloys

The fatigue behavior of the two alloys is being studied to determine the unnotched and notched strengths at -110 F, room temperature, and 550 F, and especially to observe any effect of exposure on the fatigue behavior. Table 5 lists conditions for which S-N data are being generated. Some data for Conditions 1, 2, 4, and 5 were presented in the second quarterly report. A sufficient number of experiments have been run for each of the Conditions 1 to 16 so that S-N curves can be estimated. Notched titanium alloy specimens, exposed under load at 550 F for 1000 hours, will become available early in May for determination of the effect of exposure on the fatigue strengths of that alloy.

Concerning the possible effects of stress-temperature exposure on the static and fatigue strengths of the two materials, comparison of the data for Conditions 9 and 6 shows for the AM 350 steel an apparent lessening (of the order of 5 ksi) of fatigue strength at -110 F, by the exposure for 1000 hours at 550 F and 40-ksi stress. However, the data for Conditions 10 and 8 indicate no appreciable effect on strength in fatigue at 550 F by the previous stress-temperature exposure. Additional experiments, which are planned for the next quarter with specimens exposed for some 3000 hours, should help to confirm the apparent trend of fatigue strengths with previous exposure.

The data obtained so far on notched and unnotched specimens show high notch sensitivities, especially for the Ti-8Al-1Mo-1V alloy. Fatigue-strength reduction factors (K_f), calculated as the ratio of alternating stress components — unnotched to notched — in some cases are apparently greater than the K_T values. K_f-values calculated for both alloys at room temperature and at 10^7 cycles are markedly greater than K_T (= 4.0). The very high K_f values may arise partly from uncertainty in the fatigue limits because of statistical scatter in the experimental results. Additional experiments, especially with unnotched specimens, will permit estimating the fatigue strengths within narrower limits and might result in lower values of K_f. Some experiments are being considered to investigate the possibility that high residual stresses may have been produced in the notched specimens, and that these might have resulted in low notched fatigue strengths.

In addition to selected experiments planned to establish fatigue strengths at long lives within narrower limits, and to otherwise complete the S-N plots already started, S-N plots will be generated for Conditions 16, 17, and 18 of Table 5 pertaining to notched Ti-8Al-1Mo-1V alloy specimens.

TABLE 5. CONDITIONS FOR WHICH S-N CURVES WILL BE DEVELOPED

Condition	Specimen Type	Test Temperature, F	Mean Stress, 10^3 psi	Exposure Time Under Load at 550 F, hours
		AM 350 Steel		
1	Unnotched	RT	20	None
2	Unnotched	RT	40	None
3	Notched	RT	20	None
4	Notched	RT	40	None
5	Unnotched	-110 F	40	None
6	Notched	-110 F	40	None
7	Unnotched	550 F	40	None
8	Notched	550 F	40	None
9	Notched	-110 F	40	1000
10	Notched	550 F	40	1000
		8Al-1Mo-1V Titanium Alloy		
11	Unnotched	RT	25	None
12	Notched	RT	25	None
13	Unnotched	-110 F	25	None
14	Notched	-110 F	25	None
15	Unnotched	550 F	25	None
16	Notched	550 F	25	None
17	Notched	-110 F	25	1000
18	Notched	550 F	25	1000

Fractographic Examination of Fatigued Specimens

Unexposed AM 350 steel specimens were fatigue cracked at three different stress levels, i.e. 15,000 psi, 30,000 psi, and 55,000 psi, superimposed upon a mean stress of 40,000 psi. The central notch was 0.122 inch long and had a K_t value of about 7.8. The total crack length (tip to tip) as a function of the number of cycles is shown in Figure 7; the discontinuities in the curves reflect load readjustments to keep the net section stress within ±10 per cent of the indicated values.

Replicas for examination in the electron microscope were taken from the fatigue-crack surfaces at the positions indicated by the arrows in Figure 7. Electron micrographs of some of the areas examined are shown in Figures 8 and 9. Note the striations

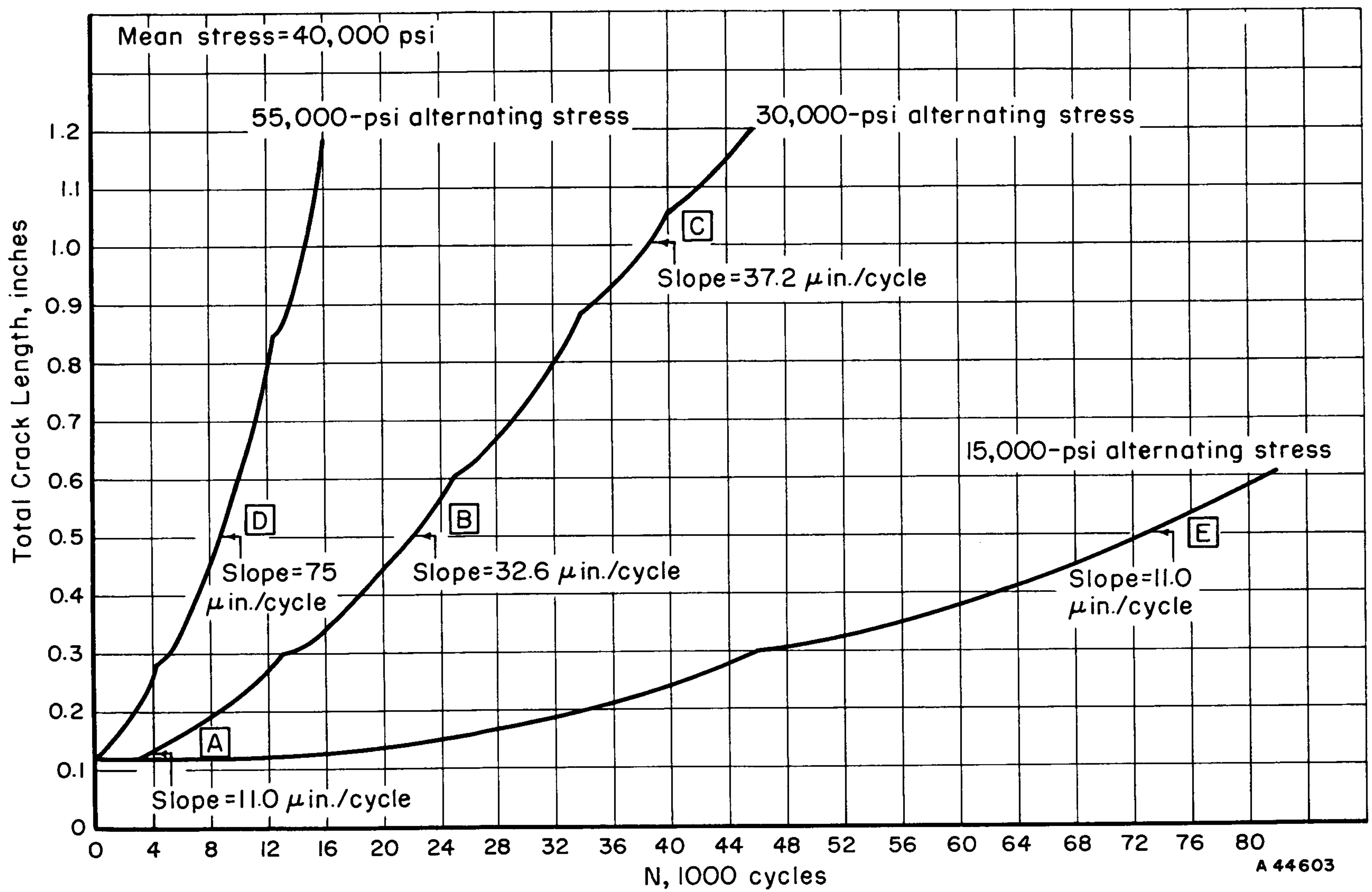


FIGURE 7. FATIGUE CRACK PROPAGATION CURVES FOR AM 350 STEEL SHEET SPECIMENS, 2 INCHES WIDE BY 0.051 INCHES THICK

Stresses were maintained within ± 10% of the values indicated; the discontinuities in the curves are the result of load readjustments.

11,250X E233D

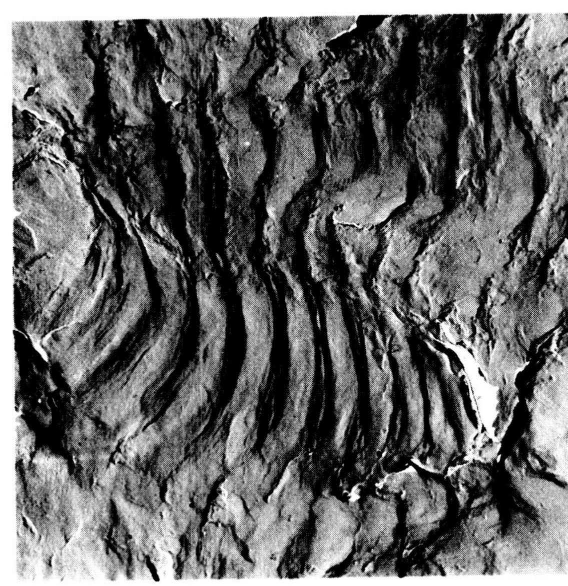
a. Position A

11,250X E225B

b. Position B

11,250X E226E

c. Position C



11,250X E225E

d. Position B

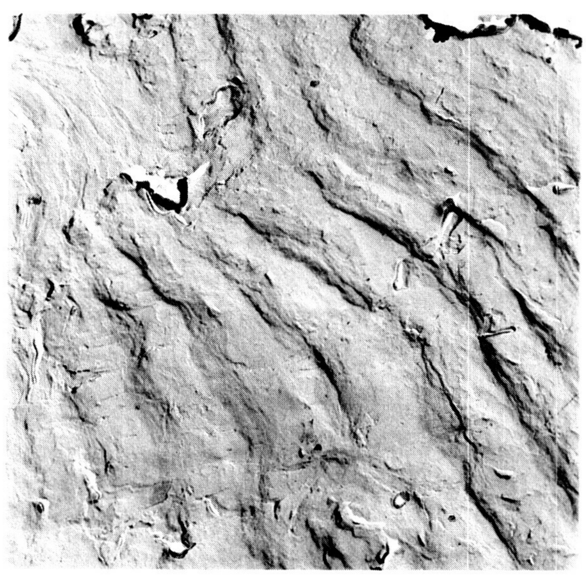
FIGURE 8. ELECTRON MICROGRAPHS OF REPLICAS OF AM 350 FATIGUE FRACTURE SURFACES, FATIGUED AT 40,000 PSI MEAN STRESS AND 30,000 PSI ALTERNATING STRESS

11,250X E224C

a. Position E

11,250X E224E

b. Position E



11,250X E233C

c. Position D

FIGURE 9. ELECTRON MICROGRAPHS OF REPLICAS OF AM 350 FATIGUE FRACTURE SURFACES, a AND b FATIGUED AT 40,000 PSI MEAN STRESS AND 15,000 PSI ALTERNATING STRESS, AND c FATIGUED AT 40,000 PSI MEAN STRESS AND 55,000 PSI ALTERNATING STRESS

in the surface, typical of fatigue failures in a wide variety of metals. These striations were detected across the entire thickness of the specimens; no evidence of shear lips was found. Other interesting observations concerning the fracture surface appearance include:

(1) The striations generally proceed directly away from the crack origin; however, they sometimes curve and move at an angle to the over-all direction of crack propagation for short distances.

(2) Areas exhibiting striations are frequently surrounded by areas of relatively flat fracture in which no striations are apparent (see Figure 8b).

(3) The striation spacing is not uniform; it frequently varies by a factor of 3 or more in closely adjacent regions of the fatigue surface.

(4) Major striations are sometimes observed to consist of a number of minor striations (see Figure 8d).

(5) The striation spacing frequently is decreased in the vicinity of inclusions.

These observations suggest that fatigue-crack growth in AM 350 steel is not as smooth and continuous as indicated by the curves of Figure 7.

To examine the relationship between the number of cycles and the number of striations, the crack-propagation rates (μin./cycle) shown in Figure 7 were compared with the striation spacings (μin./striation) obtained from electron micrographs. Dividing the crack-propagation rate by the striation spacing gives the number of striations per fatigue cycle. The results are as follows:

Location	Striations/Cycle
A	0.3 to 1.0
B	0.7 to 2.1
C	0.8 to 3.5
D	0.9 to 4.5
E	0.9 to 2.3

These results suggest that each striation represents one fatigue cycle, as has been reported by several investigators. Additional studies are in progress.

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